

Full paper

Extra Patient Movement During Mammographic Imaging: An Experimental Study

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ABSTRACT

Objectives: To determine if movement external to the patient occurring during mammography may be a source of image blur.

10 Methods: Four mammography machines with seven flexible and nine fixed paddles were
evaluated. In the first stage, movement at the paddle was measured mechanically using two
calibrated linear potentiometers. A deformable breast phantom was used to mimic a female
breast. For each paddle, the movement in millimeters and change in compression force in
Newton was recorded at 0.5 and 1 second intervals respectively for 40 seconds with the phantom
15 in an initially compressed state under a load of 80N. In the second stage, clinical audit on 28
females was conducted on one mammography machine with the 18x24cm and 24x29cm flexible
paddles.

Results: Movement at the paddle followed an exponential decay with a settling period of
20 approximately 40 seconds. The compression force readings for both fixed and flexible paddles
decreased exponentially with time while fixed paddles have a larger drop in compression force
than flexible paddles. There is a linear relationship between movement at the paddle and change
in compression force.

25 Conclusions: Movement measured at the paddle during an exposure can be represented by a
second order system. The amount of extra-patient movement during the actual exposure can be
estimated using the linear relationship between movement at the paddle and the change in
compression force.

30 Advances in knowledge: This research provides a possible explanation to mammography image
blurring caused by extra patient movement and proposes a theoretical model to analyze the
movement.

Key words: mammography, breast compression, paddle motion, damping, blurring and

35 thixotropic behavior

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90 INTRODUCTION

Since the introduction of full field digital mammography (FFDM), a number of breast imaging centers have identified blurred images through local audit. Individual centers have taken steps to reduce blurring through improving patient positioning, limiting the potential of patient movement and arresting patient respiration for the exposure duration, but blurring persists.

95 Despite many centers anecdotally reporting the persistence of blurred images few reports have been published considering the isolation of the causal factors [1]. Persistent blurring was probably present on conventional film mammography but due to improvements in contrast resolution in FFDM and the ability to magnify images, it may have become more apparent [2,3].

Blurring may obscure significant breast pathology and can necessitate repeat imaging thus
100 increasing the radiation dose received by patients and raising their anxiety. Figure 1 shows a left mediolateral oblique mammography image acquired on a Hologic Selenia Dimensions unit using a 18X24cm paddle. The image required repeating because it was not possible to determine whether pathology was present in the blurred areas. The repeat, sharp image demonstrated the presence of pathological features in this instance.

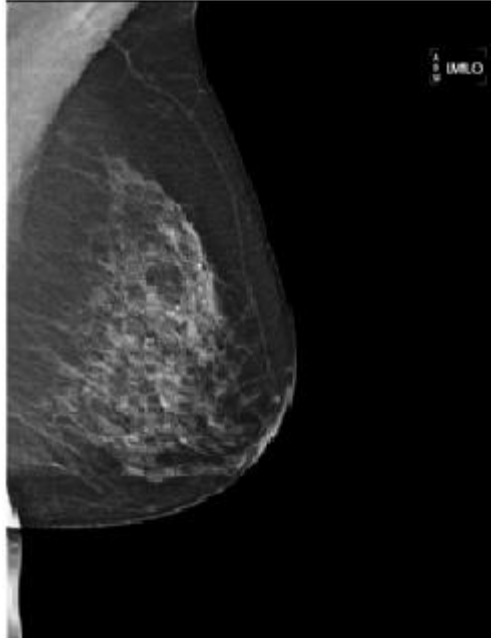


Figure 1. The image demonstrates significant blurring particularly around the junction of the mid to lower zone.

Despite reports of blurred images in UK National Health Service Breast Screening Programme (NHSBSP) quality assurance forums, there is currently a paucity of literature surrounding this topic and only two publications have been found regarding digital mammography image blurring [4,5]. Hogg et al reported a potential relationship between a perceived increase in blur and the use of FFDM systems and suggested this could be due to paddle motion or tissue relaxation [4]. They further suggested that blur was seen in up to 20% of screening mammograms even if deemed to be of adequate diagnostic quality. Choi et-al reported FFDM patient related motion to occur in only 0.4% of examinations and attributed this to longer exposure times. Motion artifacts were found to occur more commonly on linear grids rather than the crossed air type [5].

A number of hypotheses relating to causal factors for blur include inadequate compression, patient and paddle movement. In a multicentre study on paddle distortion Hauge et al. [6]

noticed that the paddle moved for a significant period of time after compression force had ceased being applied. Research by Kelly et al. [7] suggested that image blurring may be induced by compression paddle movement during the image acquisition process. This led to the hypothesis that during an exposure there is significant movement external to the control of the patient, called extra patient movement. The extra patient movement may be caused by the reduction in the compression force during the exposure, resulting in a change in compressed breast thickness and lead to the movement of the breast tissue. Another possibility is that the breast exhibits thixotropic behavior. This is supported by Geerligs et al. [8] who suggested that the adipose tissue undergoes structural changes when mechanical loading is applied. Therefore traditional strategies to reduce image blur, related to reducing controllable patient movement, called intra patient movement, may be inadequate. In light of that, a multicentre study was conducted to test our hypothesis and to propose a theoretical model to analyze and predict extra patient movement.

METHODS AND MATERIALS

This study was divided into two stages with the aim to determine the expected extra patient movement during exposure. In the first stage, a theoretical model of paddle movement was developed from the breast phantom study. In the second stage, a clinical audit was undertaken to assess compression force reduction in-vivo. The theoretical model developed in the first stage was then applied on the clinical audit data in the second stage to predict the average extra patient movement in the clinical environment.

Stage 1: Breast Phantom Study

Four mammography machines in three hospitals with seven fixed and nine flexible paddles (Table 1), calibrated to give compression force in Newtons (N), were included in this study.

140 Routine equipment quality assurance (QA) had been performed on the machines and the results
 145 complied with manufacturer specifications [9, 10]. Flexible paddles often have a spring-loaded
 system to allow compression force to be equally shared among the anterior and posterior parts of
 the paddle for more uniform compression (figure 2). However, the posterior part of many fixed
 paddles is fixed firmly to the supporting framework, which only allows movement in the anterior
 part when compressed (figure 3).

Table 1. List of mammography units and paddles used in this study

Hospital	Mammography unit	Paddle size and type	Number of Units Tested
A	Hologic Selenia Dimensions	18x24cm, fixed 18x24cm, flexible 24x29cm, fixed 24x29cm, flexible	2
B	Hologic Selenia Dimensions	18x24cm, fixed 18x24cm, flexible 24x29cm, fixed 24x29cm, flexible	1
C	Hologic Selenia Dimensions	18x24cm, fixed 18x24cm, flexible 24x29cm, fixed 24x29cm, flexible	1



Figure 2. Hologic Selenia 18x24cm flexible paddle



Figure 3. Hologic Selenia 18x24cm fixed paddle

150 ***Deformable breast phantom and compression force***

A deformable female breast phantom (Trulife, Sheffield, United Kingdom) was used to investigate paddle movement. The phantom had similar compression characteristics to the human female breast, with a pre-compression thickness of 130mm. The phantom breast was encapsulated in a thin layer of latex and attached to a rigid supporting board via a semi-mobile

155 mounting system (figure 4).



Figure 4. Deformable breast phantom mounted to rigid supporting board.

As shown in figure 4, the rigid supporting board was kept firmly against the paddle and detector using a ratchet strap. The ratchet strap prevented the breast slipping out of the paddle and detector region when compression force was applied. The strap therefore acted similarly to a human female leaning against the paddle and detector to prevent breast slippage when compression force was applied.

The semi-mobile mounting system allowed the breast phantom to have minor movement on the rigid supporting board, in a fashion similar to a real breast on the pectoralis major muscles [11]. The latex coating gave a level of rigidity to the phantom breast, similar to skin, which limited lateral and vertical motion. When compressed the breast phantom allowed the paddle to respond in a fashion similar to compressing real breast tissue. This meant that the distal end (chest wall)

of the paddle was slightly elevated when fixed paddles were used; as expected this elevation was more pronounced when flexible paddles were used.

For each paddle, the phantom was compressed to approximately 80N by applying the
 170 compression force slowly using the foot pedal initially and then hand winding to fine tune the
 compression force when the reading approached 80N. The 'machine given' compression force
 readings were recorded at 1 second intervals for 40 seconds after the compression force applied
 by the practitioner ceased. The schematic diagram for the experimental configuration is shown in
 figure 5.

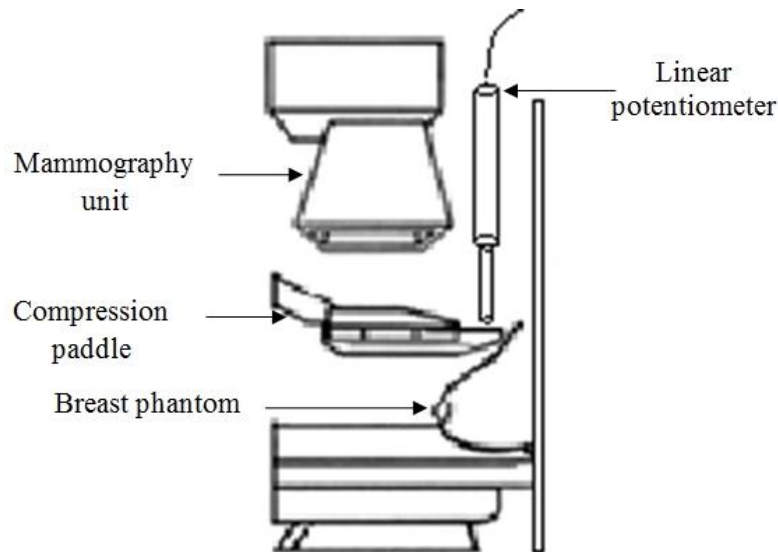


Figure 5. Schematic diagram showing the experimental configuration

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Paddle movement

The paddle movement was measured mechanically using two calibrated linear potentiometers (CLS1321) (Indianapolis, USA) with a measurement range of 150mm and a non-linearity of 0.15%. The linear potentiometers were placed at the paddle corners adjacent to the chest wall to

180 measure movement in the vertical direction. For each paddle, the measurement was repeated three times to minimize experimental uncertainties; six potentiometer readings were therefore taken for each paddle. The rationale for locating the linear potentiometers at the paddle corners, adjacent to the chest wall, is based on the research findings from Hauge et al [6]. Hauge noticed that most of the paddle distortion was found at the chest wall side of the paddle, which suggests
185 that most movement might occur in this region.

Data logging system

Paddle movement in millimeters (mm) was recorded at 0.5 second intervals for 40 seconds by a custom-made data logging system provided by Mass Measuring Ltd (Manchester, United Kingdom). A pilot study identified that movement stabilizes after approximately 30 seconds, on
190 this basis it was decided to record readings for a period of 40 seconds; it was also considered that any clinical exposure will be much shorter than the threshold set so any potential clinical impact should be fully described in this time frame. A 16-bit analog to digital converter (ADC) was used in the data logging system. The data logging system serves three purposes: to calibrate the linear potentiometers before measurements are taken, to create a time log of the linear
195 potentiometer readings, and to export the recorded potentiometer data into excel spread sheet format via a USB port for subsequent analysis.

Error analysis

Measurement Resolution

200 Because the ADC used in the data logging system is a 16 bit controller and the measurement range of the linear potentiometer is 150mm, the smallest division that can be measured by the linear potentiometer is 0.002mm. The uncertainty is assumed to be uniformly distributed [12].

The standard uncertainty can be found by dividing the half-width (0.001mm) by square root of 3, giving $u_r = 0.0007\text{mm}$.

205 *Non-linearity*

The linear potentiometer has a non-linearity of 0.15% (0.23mm). The uncertainty is assumed to be uniformly distributed [12]. The standard uncertainty can be found by dividing the half-width (0.23 mm) by square root of 3, giving $u_n = 0.1 \text{ mm}$.

The combined standard uncertainty from all these factors

210 $u_t = \sqrt{u_r^2 + u_n^2}$, giving $u_t = 0.1\text{mm}$. For 95% level of confidence, the linear potentiometer standard uncertainty is $\pm 0.2\text{mm}$.

Data analysis

The potentiometer readings only indicate the relative position of the paddle at a specific time; the actual paddle movement was determined by subtracting the final position of the potentiometer at
 215 40 seconds from the current position at time t_x . It was noticed that, on occasion, paddles tilt during the application of compression force and the paddle movement measured by one potentiometer can be different to the other. The term ‘paddle tilt’ used in this paper is defined as the inclination of the compression paddle in the frontal plane. To compensate for paddle tilt, the two potentiometer readings were averaged to provide a mean value for the paddle’s movement in
 220 the vertical direction.

Stage 2: Clinical Audit

A relationship between paddle movement and the change in compression force was derived using the experimental phantom data from stage 1. Practical calibration factors were determined

from the paddle movement - change compression force relationship on a Hologic Selenia
225 Dimensions machine with the 18X24cm and 24X24 flexible paddles. The calibration factors
were then applied on the data from the clinical auditⁱ in stage 2 to estimate the amount of paddle
movement which might be present during the actual exposure of 28 female patients on the same
mammography unit. Compression force at the start of each exposure and compression force at
the end of each exposure were recorded for each patient.

230 ⁱ *Approval was granted by the hospital to carry out this audit.*

RESULTS

Stage 1: Phantom study

Paddle movement

235 Movement at the paddle for fixed and flexible paddles was plotted against time
(figures 6 to 9). As can be seen in figures 6 to 9, the movement decreases exponentially without
oscillation and fixed paddles have a shorter average settling time than flexible paddles. The error
bars in figures 6 to 9 are the standard uncertainty of the measurement which is calculated in the
error analysis section.

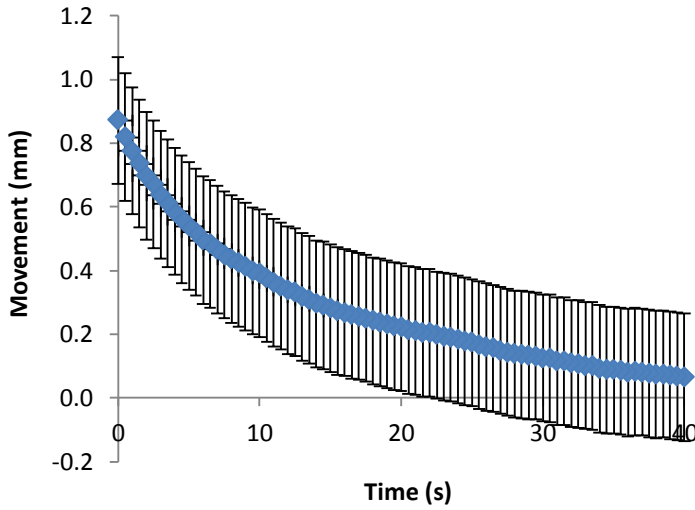


Figure 6. Movement-time curve for 18x24 cm fixed paddles. Error bars show the instrumentation error.

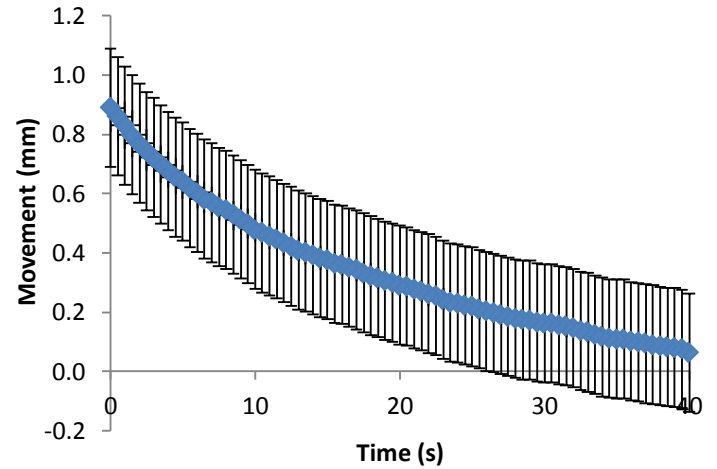


Figure 7. Movement-time curve for 18x24 cm flexible paddles. Error bars show the instrumentation error.

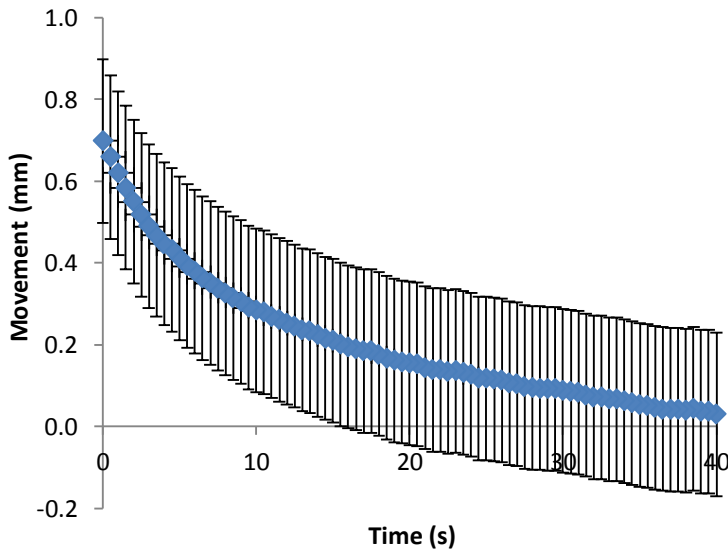


Figure 8. Movement-time curve for 24x29 cm fixed paddles. Error bars show the instrumentation error.

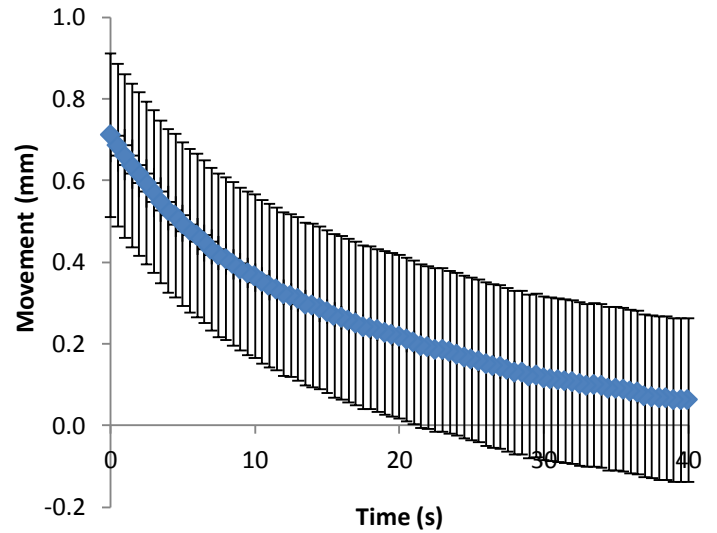


Figure 9. Movement-time curve for 24x29 cm flexible paddles. Error bars show the instrumentation error.

The average paddle movement for 18x24 cm fixed and flexible paddles in the first 10 seconds interval was 0.43mm and 0.38mm respectively which contributed to 59% and 48% of the total movement. The average paddle movement for 24x29cm fixed and flexible paddles in the first 10

seconds interval was 0.38mm and 0.32mm respectively which contributed to 61% and 54% of the total movement (Table 2). As can be seen in table 2 the rate of paddle movement for both fixed and flexible paddles is the highest in the first 10 seconds interval and drops significantly after the first 10 seconds interval.

Table 2: Average paddle movement and the rate of paddle movement over the 40 seconds measuring period mm,(mm/s)

Paddle Type	Time period (s)			
	0.5-10	10.5-20	20.5-30	30.5-40
18X24 cm fixed	0.43 (-0.044)	0.15 (-0.016)	0.09 (-0.010)	0.06 (-0.006)
18X24 cm flexible	0.38 (-0.038)	0.18 (-0.018)	0.13 (-0.013)	0.10 (-0.010)
24X29 cm fixed	0.38 (-0.037)	0.12 (-0.013)	0.06 (-0.007)	0.06 (-0.006)
24X29 cm flexible	0.32 (-0.034)	0.13 (-0.014)	0.09 (-0.010)	0.05 (-0.006)

Table 3 summarizes the maximum, minimum, average and standard deviation of paddle movement (over the settling period of 40 seconds) for the seven fixed and nine flexible paddles. The flexible paddles have slightly larger average movement than the fixed paddles.

Table 3. Summary of paddle movement across time.

Paddle size, paddle type	18x24cm, fixed	18x24cm, flexible	24x29cm, fixed	24x29cm, flexible
Maximum (mm)	1.41	0.96	0.86	0.85
Minimum (mm)	0.01	0.02	0.01	0.02
Average (mm)	0.28	0.34	0.21	0.26
Std Dev (mm)	0.25	0.22	0.18	0.18

The dynamics of mechanical systems and their controls can often be approximated to those of a second order system, for example a spring-mass-damper arrangement. In this case, the settling response of the movement at the paddle suggests second order dynamics that are damped, the standard solution for which is given by [13]:

$$x(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t}$$

260 λ_1 and λ_2 are empirically identified constants that reflect the physical properties of the paddle and breast. C_1 and C_2 are empirically identified constants that depend on the initial conditions of the system at the start of the movement. The movement equations for fixed and flexible paddles were derived using iterative fitting, minimizing the residual sum of the squares (RSS) using Microsoft Excel (Redmond, Washington, USA). The RSS values for 18x24 cm and 24 x29cm
265 fixed paddles were 0.0338 and 0.025, respectively; and for 18x24 cm and 24 x29cm flexible paddles were 0.0088 and 0.0071, respectively, which indicates only a small discrepancy between the experimental data and the proposed second order model. The general paddle movement equations for the 18x24 cm and 24x29cm fixed paddles are
 $x(t)_{18x24} = 0.392e^{-0.07t} + 0.392e^{-0.07t}$ and $x(t)_{24x29} = 0.313e^{-0.07t} + 0.313e^{-0.07t}$ respectively.
270 The general paddle movement equations for the 18x24 cm and 24x29cm flexible paddles are
 $x(t)_{18x24} = 0.431e^{-0.06t} + 0.431e^{-0.06t}$ and $x(t)_{24x29} = 0.340e^{-0.06t} + 0.340e^{-0.06t}$ respectively. The damping ratio, ζ , and natural frequency, ω_n , for fixed paddles are 1 and 0.07 rad s⁻¹, respectively, and for flexible paddles are 1 and 0.06 rad s⁻¹, respectively.

Compression force

275 The ‘machine given’ compression force readings for both fixed and flexible paddles decreased exponentially with time (figures 10-13). The average drop in compression force for 18x24cm

fixed and flexible paddles in the first 10 seconds interval was 7N and 3N respectively which contributed to 64% and 75% of the total change in compression force. The average drop in compression force for 24x29cm fixed and flexible paddles in the first 10 seconds was 6 N and 3N respectively which contributed to 67% and 75% of the total change in compression force (Table 4). The rate of change of compression force in the first 10 seconds interval is the highest for both fixed and flexible paddles and drops significantly after the first 10 seconds interval.

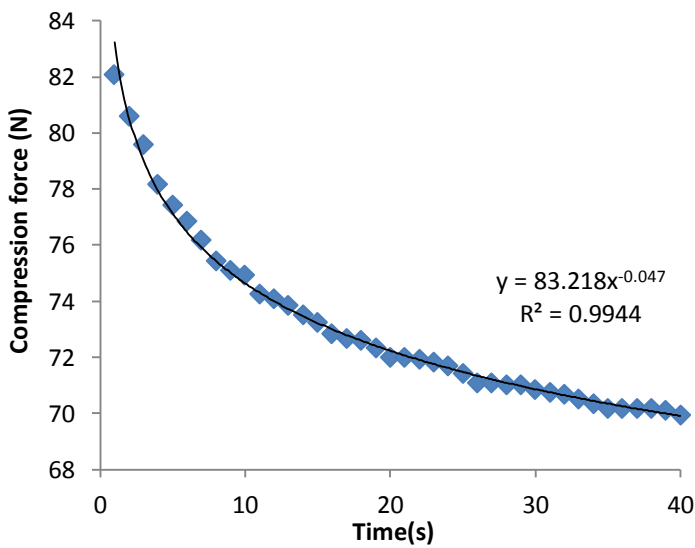


Figure 10: Compression force against time for 18X24 cm fixed paddles

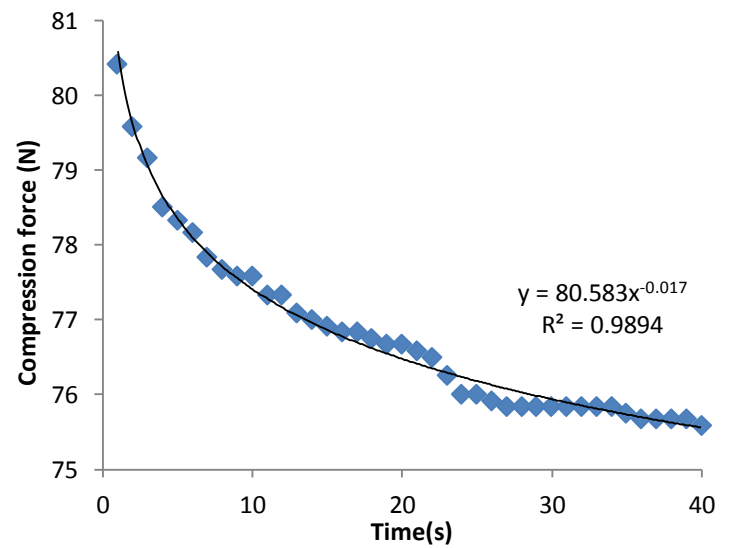


Figure 11: Compression force against time for 18X24 cm flexible paddles

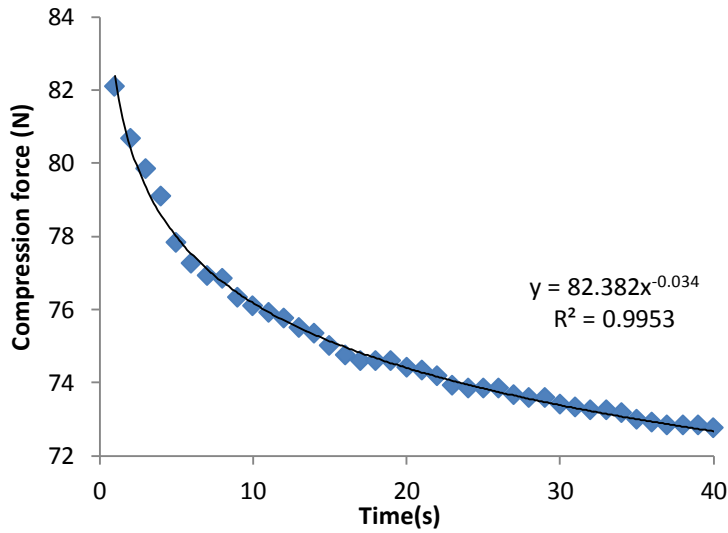


Figure 12: Compression force against time for 24X29cm fixed paddles

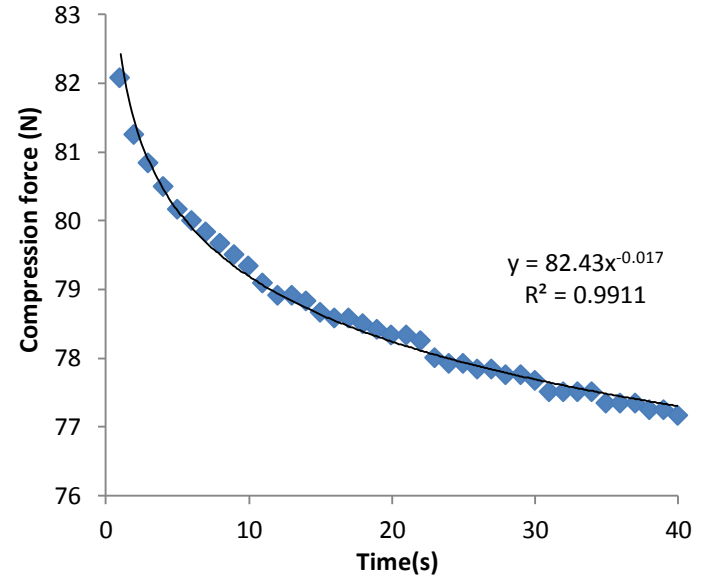


Figure 13: Compression force against time for 24X29cm flexible paddles

Table 4: Average compression force change and the rate of change over the 40 seconds

measuring period N,(N/s)

Paddle Type	Time period (s)			
	1-10	11-20	21-30	31-40
18X24 cm fixed	7 (-0.7)	2 (-0.2)	1 (-0.1)	1 (-0.1)
18X24 cm flexible	3 (-0.3)	0 (0)	1 (-0.1)	0 (0)
24X29 cm fixed	6 (-0.6)	2 (-0.2)	1 (-0.1)	0 (0)
24X29 cm flexible	3 (-0.3)	1 (-0.1)	0 (0)	0 (0)

Table 5 summarizes the maximum, minimum, average and standard deviation of average compression force drop for the seven fixed and nine flexible paddles. The fixed paddles have a larger average compression force drop than the flexible paddles.

290 Table 5. Summary of compression force drop across time.

Paddle size, paddle type	18x24cm, fixed	18x24cm, flexible	24x29cm, fixed	24x29cm, flexible
Maximum (N)	18	7	11	7
Minimum (N)	6	3	8	4
Average (N)	12	5	9	5
Std Dev (N)	3.8	1.2	1.2	1.3

Compression force Vs Paddle movement

The change in compression force was determined by subtracting the initial compression force at time zero t_0 from the current compression force at time t_x . As seen in figures 14 and 15, a proportional relationship between movement at the paddle and change in compression force was demonstrated. The calibration factors for the Hologic Selenia Dimensions unit with the 18X24cm and 24x29 cm flexible paddles were 0.1552 and 0.1304 respectively. This relationship between compression force and movement will depend on the elasticity of the breast. Our phantom has only one elasticity, unlike the female breasts which will have a range of elasticities

300 (k). Further work should bear this in mind.

Extra Patient Movement During Imaging

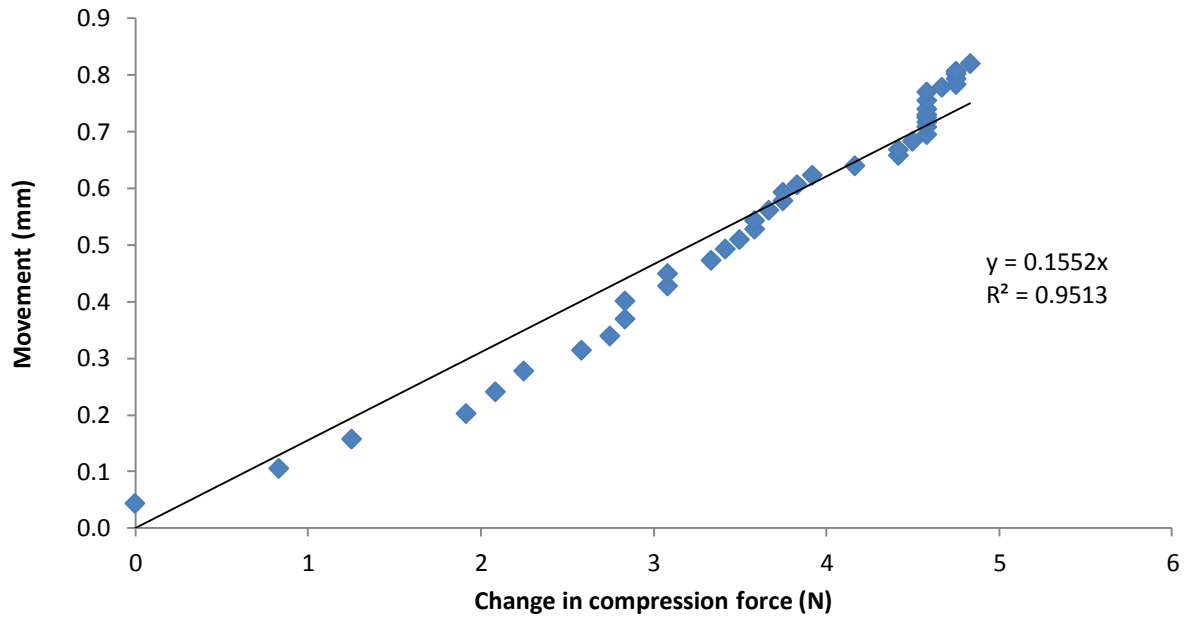


Figure 14. The relationship between paddle movement and change in compression force for 18X24cm flexible paddle.

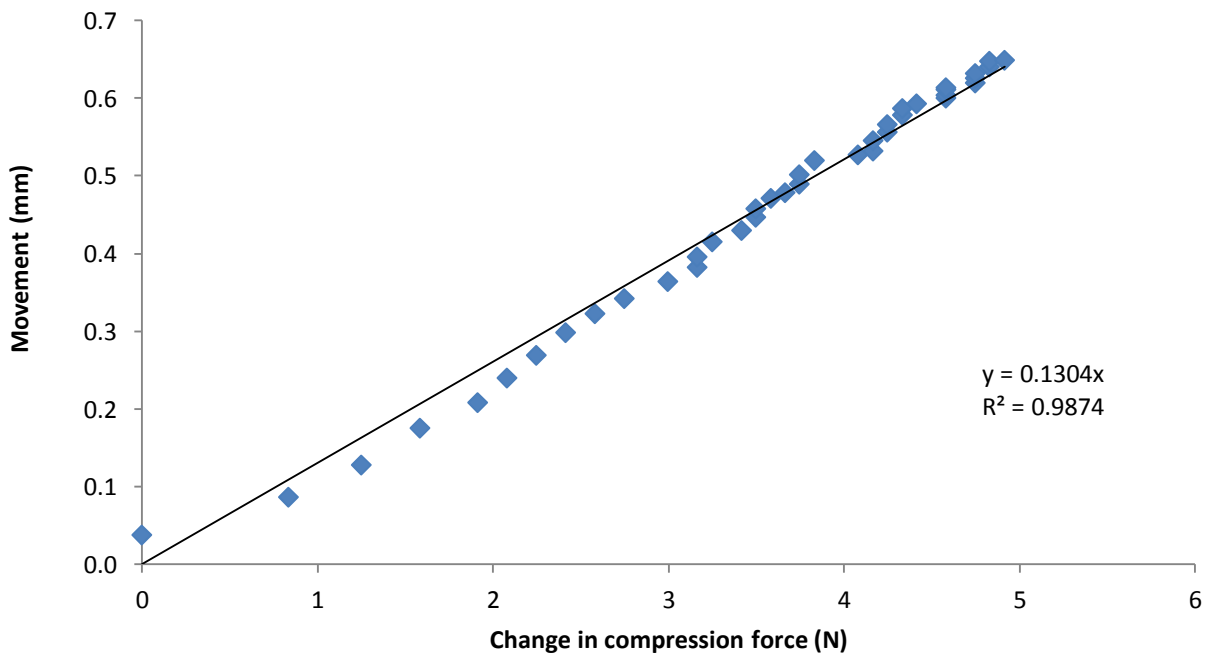


Figure 15. The relationship between paddle movement and change in compression force for 24X29cm flexible paddle.

Stage 2: Clinical Audit

Table 6 summarizes the maximum, minimum, average and standard deviation of change in compression force on the Hologic Selenia Dimensions unit used for the clinical audit using the 18X24cm and 24X29cm flexible paddles. Using the calibration factors derived from our phantom experiment the amount of movement that might be incurred during the exposure from the 28 females was predicted. The average movement for the 18X24cm and 24x29cm flexible paddles is 0.62mm and 0.61mm respectively.

Table 6. Summary of change in compression force at different time intervals

Change in compression force (N)		
Paddle size (cm)	18x24	24x29
Time interval ⁱⁱ	t ₁ - t ₂	t ₁ - t ₂
Max	9	15
Min	1	1
Average	4	4.7
Std Dev	2.70	3.6

ⁱⁱ where t₁ – point at which compression force ceases to be applied, and t₂ - point at which the exposure terminates

DISCUSSION**Study Limitations**

Linear potentiometers

Although there may be a different rate of change between the two measurement points, the difference is not significant. As can be seen in figures 16 and 17 there is only a slight difference between the paddle movement measured by the two potentiometers for fixed ($p=0.34$) and flexible paddles ($p=0.30$) this may be due to paddle tilt during the application of compression which made the potentiometers to be at slightly different levels. Since the difference between the movements measured by the two potentiometers is insignificant we average the measurements from the two potentiometers to simplify the interpretation and the presentation.

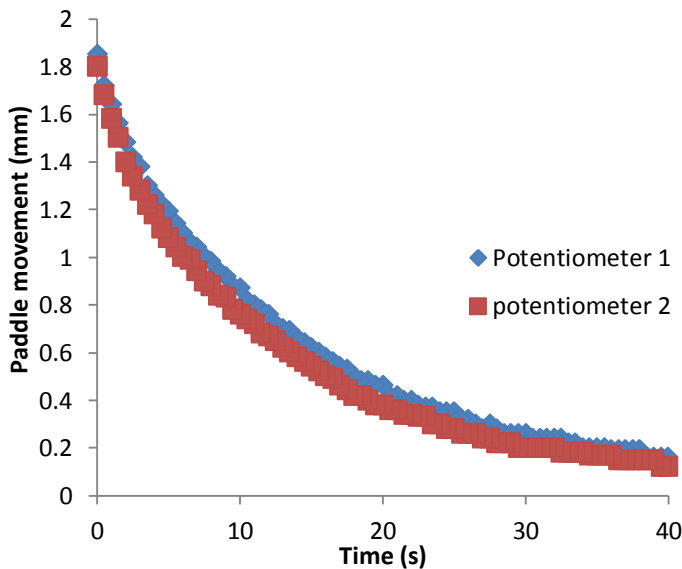


Figure 16. Paddle movement against time for a 18X24 cm fixed paddle

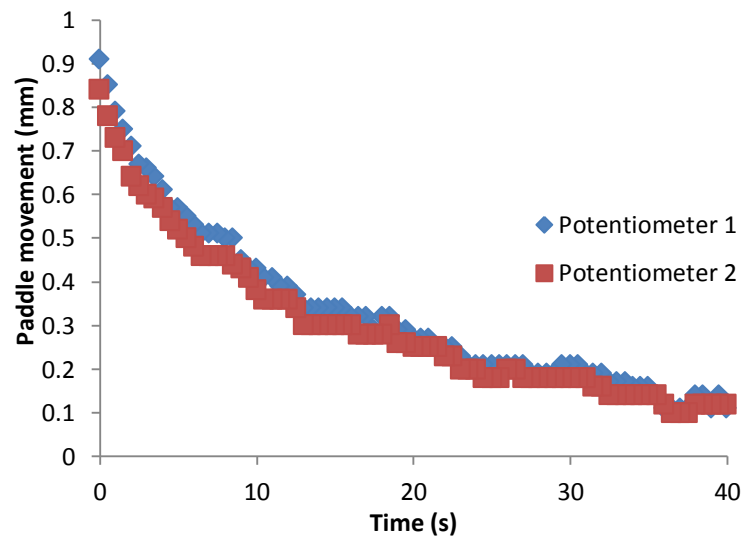


Figure 17. Paddle movement against time for a 18X24 cm flexible paddle

Compression force

As the compression force applied was not a rapid step input, the response of the breast and paddle can begin before the end of the hand winding period (start of measurement). Therefore, the recorded movement at the paddle after measurement begins may lead to an underestimation of the total movement. In extreme cases, if the winding is too slow, there would be no

exponential settling after measurement begins because it would have all happened during the
335 hand winding period. Different design of compression systems among different brands of
mammography units may play a significant role in paddle movement. In the human component
of our study only Hologic Selenia Dimensions unit was used. Consequently we suggest the study
should be repeated using a range of manufacturers to determine whether a similar effect will be
seen.

340

Paddle movement

In this study, we only recorded movement of the paddle; we did not identify exactly where the
movement occurred. But from the phantom experiment we have demonstrated there is significant
345 movement that is independent of the patient when a compressible material is used. If the
European guidelines are followed and passed there is no systematic issue with movement which
indicates the breast response to compression is the dominant factor and should be further
investigated [10]. The slightly less movement in the flexible paddles results may be attributed to
more lateral retention of the soft tissue compared to fixed paddles; however this has not been
350 verified and could be a focus of future work.

Breast phantom Vs Real breasts

Breasts vary in shape, size and composition. Our experiment only used one phantom and
consequently it did not simulate the range of female breasts. We hypothesize that different
phantom designs and female breasts would demonstrate varying characteristics due to varying
355 tissue composition and size. This is supported by the work of Geerligs et al [8] where the

mechanical properties of adipose tissue have been investigated. They reported that adipose tissue was viscoelastic with thixotropic behavior at large strains and anti-thixotropic at small strains. The material is thixotropic if the viscosity decreases with time at constant shear rate and if the viscosity increases with time at constant shear rate the material is anti-thixotropic. In
 360 thixotropic behavior structural changes occur due to mechanical loading and the longer the loading the more viscous the material becomes; anti-thixotropic materials increase viscosity over time. Further investigation of the thixotropic behavior of the breast, including glandular tissue, would be valuable in designing novel compression systems.

Perception in blurring

Paddle displacement

According to the European Guidelines for Quality Assurance in Breast Cancer Screening and Diagnosis [10], the acceptable exposure time limit for the standard breast thickness is 2 seconds. Using the general paddle movement equations developed from the breast phantom data, the estimated movement for the 2 seconds limit at the paddle 18 x 24 cm and 24 x 29 cm flexible
 370 paddles are 0.8 ± 0.2 mm and 0.6 ± 0.2 mm respectively. From our clinical audit the predicted movement during the exposure for 18 x 24 cm and 24 x 29 cm flexible paddles are 0.62 mm and 0.61 mm respectively which is quite close to the estimated value. Logically movement in the breast, along any vector that results in a lateral pixel movement of greater than 1 subtended pixel at the detector has the potential to produce blur. The impact of this will be dependent on the
 375 relative exposure time of the displaced pixel and the size of the feature of interest. Therefore considering a 6 cm compressed breast with a feature of relevance at the point of greatest geometric magnification (1.1x), i.e. the upper breast, where 1 pixel detector movement is

unacceptable e.g. microcalcifications; a vector spatial movement in the breast of 90% of the detector pixel size could result in image blur. For a 0.1mm detector pixel size a 0.09mm spatial movement could therefore result in blur. This is dependent on the displaced element being exposed long enough to produce an appreciable resultant pixel contrast and therefore rate of change, rather than absolute, movement is the more important metric.

However, presently no published data exists to demonstrate how much movement needs to occur before image degradation (blurring) will be perceived and further research is needed. With this in mind we have already commenced two projects; one using a mathematical approach to generate images which have known amounts of simulated movement; the other was published using experimental approach to identify the image blurring due to paddle movement [14]

Key to reduce blurring

For both fixed and flexible paddles the rate of change of compression force (N/s) and rate of paddle movement, ie paddle velocity (mm/s), is the highest in the first 10 seconds. The rapid change in paddle movement is probably caused by the rapid change in compression force. One of the possible explanations could be the high rate of change of compression force (decreasing) causing the rapid drop in force acting on the paddle. The decrease in force would cause the reduction in the rate of change of the paddle movement, in other words deceleration in paddle velocity.

Motion blurring is caused by the rate of paddle movement during exposure, which is caused by the changing compression force. Since the changing compression force is the important factor for motion blurring, minimizing the rate of change of compression force is the key to reduce blurring.

400 **Applications**

Delayed exposure

It is known that larger breasts require longer exposures; therefore to minimize any impact of the extra patient movement the radiographer/technologist could apply compression force more slowly. If the risk of blur is strongly suspected, or a repeat due to blur is required, a wait of 15
405 seconds from the point at which compression force ceases to be applied, to the point at which the exposure is made, would allow the rate of change of the movement to reach a minimum.

Fixed paddle Vs Flexible paddles

410 Data from the phantom experiment shows that compared with flexible paddles, fixed paddles have a shorter settling time. This may be due to the higher decreasing rate of change of compression force or 'negative jerk' in fixed paddles ie the smaller the compression force on the phantom the shorter the time taken for the paddle to settle. Therefore to reduce the risk of blur it may be advantageous for the radiographer/technologist to use fixed paddles if possible.

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System optimization

The settling time to reduce extra patient movement should ideally be as short as possible in order to reduce the possibility of inducing intra patient movement induced artifacts. In view of that, manufacturers should conduct further experiments and, if required, introduce design features that
420 lead to shorter settling times. It might also be possible for manufacturers to include a feedback system between rate of change of compression and beginning the exposure or if thixotropic processes dominate consider how the compressive force is applied.

CONCLUSIONS

425 Using a breast phantom we have shown that there is extra patient movement at the compression
paddle during mammographic exposures that can be approximated by a second order motion
equation. In vivo movement with real patients has also been proposed to be proportional to the
drop in compression force, using this derived relationship the actual motion can be estimated.

Conflict of interest statement

430 The authors have no conflict of interest.

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